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Sustainability analysis of biodiesel production: A review on different resources in Brazil

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ABSTRACT

This paper assesses 13 different inputs for biodiesel production and shows that the highest cost currently associated with the processing of residual resources, as well as their small production scale, are compensated by their smaller procurement costs, by their immediate availability in the urban centers and by their larger potential for greenhouse gas emission reduction. Biodiesel production from residues can meet all technical international specifications, even the esterification process. Data Envelopment Analysis (DEA), the methodology used in this study, allows for the building of an efficiency index up through linear programming with multiple inputs and outputs, enabling the integration of sustainable development dimensions. The experts' conclusions were arrived at through restrictions on virtual weighting, with findings that allow the grading of alternatives.

Contents

1. Introduction

In the last few years, biodiesel production and use have been increasing rapidly worldwide, growing 13 times between the years of 2002 and 2011, when it reached about 17 billion L annually [1–3]. There is great potential for its use in Brazil, as around 52 billion L of diesel oil are consumed annually [4], a fuel that biodiesel can easily replace. In 2011, approximately 17% of this fuel was imported as refined diesel oil, representing an annual outflow of foreign exchange earnings of approximately US$ 7 billion.

This renewable fuel is capable of partially or fully substituting diesel oil, both for the transport and power sectors, thus reducing the dependency on fossil fuels. No engine tuning is necessary for that. Furthermore, there are additional environmental benefits related to diesel substitution by biodiesel from residues, such as local pollutants emissions reduction.

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that. Furthermore, there are additional environmental benefits related to diesel substitution by biodiesel from residues, such as local pollutants emissions reduction.

In December 2004, the Brazilian Government decided to introduce a National Biodiesel Program, initially by replacing 2% of current diesel oil consumption, planning to reach 5% in 2013. The use of vegetable oils, from castor and palm, as main inputs of the biodiesel production were the focus of the program, and the family agriculture regime was a priority for ensuring social inclusion. Nevertheless, some difficulties in reaching the program goals were identified from the very beginning. The medium term required for harvesting palms, around six-years, and the high international prices for castor beans, made this source attractive for the international market. Endowed with technological mastery of this process through experiments conducted since the 1970s and stepped up during the late 1990s, Brazil has the capacity to produce all the required equipment and has an easily available labor force for the different process stages (rural laborers, residuals collectors and industrial workers). In terms of fatty input capacity, the country has a considerable supply of waste that can be used in biodiesel production, in addition to its well-known biodiversity and large areas available for planting.

It is important to mention that the use of energy from new vegetable oils is also beneficial to society, due to the potential for income and jobs creation. In addition, the oleaginous cultivation contributes to recovery and strengthening of unproductive soils. These species have high capacity for nitrogen recycling, allowing savings in fertilizer for other crop plantations, which is possible with edible and non-edible plant oils, according Banković-Ilić et al. [9]. The use of the edible plant oils also increases the supply of protein fraction of the oleaginous crops—an important resource for the food and animal food industries.

The group of residual resources is constituted of used oils, fatty acids obtained from the refining of vegetable oils, animal fat from slaughter-houses (bovine sebum, swine grease, fish oil and chicken fat) and sanitary sewage[1] , which are available in few places, with facilitated utilization. For the residual oils, a more elaborated logistics is necessary and is therefore more expensive.

The use of residues for biodiesel production allows to achieve high-cost products from low-cost feedstocks [18,19], as well as presents several global and local environmental benefits, if compared to the biodiesel from virgin vegetable oil.

The current pricing system cannot always reflect all the consequences of production and consumption activities, called externalities. Thus society pays its costs (external costs), or reaps its benefits (external benefits).

The renewable energy sources penetration in the energy mix has been restricted on financial grounds, while its environmental and social benefits have been neglected. Among the renewable alternatives it is also possible to find alternatives more sustainable than others. This assumption is valid either among the different sources or for different technologies or resources used in determinate source application, as for biodiesel resources, analyzed in this paper. Some sources offer bigger job opportunities, while the quantity of greenhouse gas emissions – considering the life cycle – is lower, taking into account others sources, and there are some sources that have greater input availability.

Based on Azadi et al. [22], “While biofuels have currently been regarded as a good alternative for fossil fuels, there remain many debates on their impacts on human and environment”.

This article ranks the inputs for producing biodiesel by the sustainability concept, which involves environmental, social, technological and economic aspects, through the methodology Data Envelopment Analysis (DEA).

[1] Siddiquee and Rohani [11] reviewed the various lipid extraction techniques and biodiesel production processes from municipal wastewater sludge.

2. Biodiesel production and environmental aspects

Biodiesel is the ester obtained through the reaction – esterification – of fatty acids and an active intermediator, formed by the reaction of an alcohol with a catalyst, or by the substitution of the glycerol molecule of the triglycerides with three alcohol molecules – transesterification. Independently of applied reactions and raw material, biodiesel should have physical–chemical characteristics similar to mineral diesel, in order to be able to replace it. Considering Atabani et al. [24], “physical and chemical properties of biodiesel produced from any feedstock must comply with the limits of ASTM and DIN EN specifications for biodiesel fuels”.

Since 1998, several research teams have been working on the technological development of the biodiesel production process in Brazil [20,21] and have already more than twenty input options, blending methanol and ethanol, using acid and alkaline catalysts, selected in accordance with the input characteristics.

Biodiesel production contributes to increasing the renewable energy supply, since most of the reagents originate from biomass. In this way, the use of biodiesel adds to reach the goals of the Climate Change Brazilian Policy, PNMC[2], which states the GHG emissions limits, while stimulating the development of low carbon technologies to the Energy Sector [25]. Table 1 shows pollutant emission alterations when pure biodiesel is substituted for mineral diesel oil.

NO [28] reinforced that biodiesel usually promotes an increase in NO_x emission and a decrease in HC, CO and PM emissions compared to diesel. Furthermore, this paper related that a diesel engine without any modification would work perfectly on a blend of 20% vegetable oil and 80% diesel fuel without damage to engine parts.

Moreover, burning biodiesel along with mineral diesel favors mercaptans[3] oxidation, transforming them into sulfur dioxide, a product more volatile and less harmful to living beings, thus benefiting especially urban inhabitants.

COPPE/UFRJ has been producing biodiesel through the esterification reaction, utilizing foam from the ETE's (Sewage Treatment Stations) sewer. The aim is for plants to be installed in all the continents for the utilization of this residual resource. By foam, read the over-swimming stage of the sewage, basically composed of organic matter insoluble in water, especially fatty matter. This oily stage is composed of more than 80% (in dry weight) carboxylic acids derived from the decomposition of various triglycerides and soaps present in the sewage. It is relevant to point out that, through process optimization, all samples of residual biodiesel meet the established standards of the Brazilian Regulator Agency to Oil Industry (ANP[4]), in its Resolution ANP 04/2012.[5] Through compliance, the possibility of problems with the carbon deposits, inflammability and loss in burning efficiency, is practically eliminated.

[2] The Climate Change Brazilian Policy was established by Act 12.187/2009 and regulated by Decree 7.390/2010.

[3] Mineral diesel oil has a substantial sulfur content in the form of mercaptans, extremely harmful substances to the local environment, including health. Mercaptans come in the form of atmospheric emissions derived from diesel engines' discharge, especially when working outside the normal range (partings and decelerations), and on excessive quantities, when the systems are not tuned.

[4] ANP: Agência Nacional de Petróleo, Gás Natural e Biocombustíveis—Brazil's National Petroleum Agency.

[5] It is relevant to point out that ester content limits is the only requirement that residual biodiesel cannot reach yet.

Table 1
Biodiesel emissions in comparison with diesel oil.
Source: Authors based on T.I.E.P. [26] data and Ref. [27].

Pollutant	Increase/reduction	Percentage (%)
Greenhouse gases	Reduction	90–100
Sulfur oxides	Reduction	98
Particulate matter	Reduction	50
NO_x [26]	Increase	13

In the case of utilization of fatty matter of residual origin as a main resource, the carbon dioxide emission from the burning of the biodiesel share relative to biomass is reabsorbed by the new crop. However, the avoided CH_4 emission on the land farm should be taken in consideration, as the residual resource (the oil used or the sewage foam) is normally disposed of in sanitary land farms, where it decomposes into an anaerobic system, emitting methane, as do the other residues. This gas has Global Warming Potential (GWP) 21 times higher than carbon dioxide, for a period of 100 years. Considering the methane emission originating from anaerobic decomposition of residual resources, the GEE emissions reduction of methyl biodiesel of residual resources corresponds to 96% [21].

3. Material and methods

This paper evaluated the possible combinations of raw material sources used for biodiesel production, according to the five dimensions of Sustainable Development: economic, technological, environmental, social and operational. The analysis selected necessary inputs and outputs that could be expressed numerically in absolute values. The indicators considered represent the five dimensions: "Investment Cost" (economic dimension), "O&M—Operation and Maintenance" (technological dimension), "Greenhouse Gases Emissions" (environmental dimension), "Potential Job Creation" (social dimension) and "Potential Production" (operational dimension).

In this way, it is necessary to use assessment methodologies that can handle multiple inputs and products, known as multi-criteria analysis, which can be grouped into four categories: weighting methods, sequential elimination methods, mathematical programming methods and spatial proximity methods. The Simple Additive Weighting is the most common technique applied internationally. This is a qualitative–quantitative method which was compared by Oliveira [5] to Data Envelopment Analysis (DEA), the quantitative method based on linear programming. This comparison showed that both techniques are equivalent and the present team has therefore adopted the quantitative technique to carry out their analysis, as already applied by Oliveira et al. [10] and La Rovere et al. [23]. The DEA Method has therefore been selected in this paper to evaluate the sustainability of the biodiesel production in Brazil.

Brazilian conditions allow the utilization of various resources that can be divided into three basic groups: residuals, extractives and cultivation. The latter can also be fragmented into long-term culture and annual culture. Annual cultures may be mechanical or manual labor intensive. In this paper, the application of the Data Envelopment Analysis (DEA) modeling considered the following inputs:

- Residuals resources: frying oil, animal fats (tallow, lard, and chicken fat), fatty acids and scum.
- Extractives: babassu, buriti, and Brazilnut.
- Perennials (Long term culture): palm and coconut
- Annual mechanized cultivation: soybean and sunflower.
- Annual cultivation—intensive in manual labor: castor bean.

Based on the availability of 50 million ha of deforested area on the forest "border"[6] [5] and 91 million ha of idle areas [6], it is considered that the vegetable resources may satisfy the demand for biodiesel production in Brazil. Taking all this available area into account, and assuming an annual average productivity of 4,500 t/ha for palm oil and 750 kg/ha for the other oleaginous crops [7], Brazil's potential can be estimated to reach around 300 billion L of biodiesel per year. This figure exceeds up to six times the current diesel national consumption and represents about a quarter (22%) of the current global diesel oil consumption levels, at 1.4 trillion L [8]. Even though a single-crop approach is not desirable, this potential underscores the need for Brazil to define the role that it intends to play on the emerging market.

Agricultural activity does not require any specific professional qualification, which means substantial job offerings, of over 7.5 million[7], much more than the use of residues for biodiesel production can offer.

Even with its small scale production of 2.5 billion L/yr [12–17], or 5% of the current mineral diesel consumption in Brazil, this resource is immediately available, since it does not need to be cultivated, as well as counting on competitive costs, as they are sometimes sent to cesspools, where there is a charge for its disposal, and its utilization may represent a negative cost of this resource.

It is important to apply the DEA to this case study in order to organize the vast amount of data and sources the research had to deal with. The team therefore took into account the first results obtained by DEA and applied a multi-criteria methodology to go deeper in the analysis. A group of indicators that could reveal the sustainability of the biodiesel production by sources in Brazil was chosen.

Table 2 shows the values used for each of the selected criteria. The five columns correlate among themselves. In terms of jobs creation, for example, we can notice that palm oil creates 300 times more jobs than sunflower seed production: (30 employments for 1 million L/yr of palm oil and 0.1 employments for 1 million L/yr of sunflower seed).

To perform the modeling for the use of residual resources for biodiesel production it was necessary that the negative values related to Greenhouse Gases Emissions be eliminated. Thus, one factor was added to all possible combinations of sources, so that the lowest value for this criterion would correspond to the unit.

The application of Data Envelopment Analysis (DEA) was performed with the goal of providing conclusive results about the comparison of all inputs simultaneously.

The values shown in Table 2 were applied to the classic DEA–VRS model, with orientation for maximization of outputs, obtaining ten efficient alternatives.

There are important differences between the classic DEA and VRS models. The classic DEA applies no weighting either among or within the dimensions. The VRS model is an upgrading of the classic DEA. For each dimension, all the inputs are weighted by the model to correlate different magnitudes and scales of different sources. For example, if one considers six sources in the environment dimension, the sum will be 100% and the model will calculate each weight for each source. If we put 13 sources in the same environment dimension, the model will adjust the weights to get the same 100% for the dimension as a whole and

[6] This region is known as "Deforestation Arc".
[7] Extrapolation based on data from Oliveira et al. [10] on the number of jobs per year-hectare multiplied by the available area, obtained from the same data source–palm farming: five jobs per hectare.

Table 2
Biodiesel production from different inputs: Evaluation of five indicators.
Source: Authors based on Oliveira et al. [10].

Inputs raw materials	Alternative energies	Greenhouse gases (kg CO_2 eq/L)	O&M cost (R$/L)	Investment cost (R$/L)	Quantity (million L/yr)	Number of jobs
Residuals	Lard+chicken fat	1.086	2.463	0.076	594	1188
	Frying oil	1.086	1.698	0.076	259	25,900
	Scum	1.086	1.027	0.106	39	78
	Tallow	1.086	2.463	0.076	1284	2568
	Greases	1.086	1.141	0.091	62	124
Annual	Castor bean	3.016	2.209	0.076	58	31,160
Annual Mechanized	Soybean	3.016	2.545	0.076	2594	259
	Sunflower seed	3.016	3.016	0.076	570	57
Extractivism	Brazilnut	2.966	9.664	0.091	250	50,000
	Babassu	2.966	6.15	0.076	1700	1,000,000
	Buriti	2.966	5.965	0.751	1200	240,000
Perennials	Palm	3.016	1.817	0.65	50,000	1,500,000
	Coconut	3.016	5.264	0.65	4750	200,000

to be possible to compare all the considered sources inside the dimension as well. Each dimension can thus be analyzed separately allowing conclusions as to what is the best source for that dimension. The VRS is related to one dimension but not to get weighting among different dimensions.

However, many had zero weighting zero, associated with at least one of the variables under analysis[8] , which amounts to disregarding this variable in the model. In order to avoid these distortions, restrictions were introduced to weights. A more user-friendly alternative to interact with the specialist is to consider restrictions on the virtual weights, because the limits are established through shares in the total virtual inputs (outputs), regardless of the scales used.

It is also worthwhile to stress that, due to the ample heterogeneity of magnitudes of variables, which undermines the feasibility of the Linear Programming Problems (LPPs) it was decided to consider only the restrictions on weights for the DMU under observation. Following consultations with specialists, the following weight ranges were assigned: 20–50% for the inputs and 30–60% for the outputs.

4. Results

Table 3 presents the results of the DEA model with the restrictions on virtual weights.

In the DEA classical model, ten alternatives reached maximum efficiency. The biodiesel of frying oil was used as a benchmark[9] for 12 Alternative Energy Sources in the set, with tallow and palm oil used for nine, babassu used for five, lard+chicken fat and soybean used for four, while scum, greases, castor bean and sunflower was used for three. Brasilnut, buriti and coconut complete the sequence.

Considering the restrictions on weights model, the biodiesels made from frying oil, scum, greases and Palm oil are efficient. The biodiesel made from frying oil and palm oil was used as a benchmark for seven Alternative Energy Sources in the set, with scum and grease used for three.

The biodiesels with animal fats and babassu oil reach efficiency levels of over 91%. Castor bean obtained 80% while soybean and sunflower oils was over 74%. Brazilnut aims 56% of efficiency, coconut goals 33% and buriti was 28%.

Thus, considering both the residues and vegetable oil as inputs, the National Policy priorities for the biodiesel production and consumption should be established as follows:

–First assessment: without restrictions:

1. Frying oil;
2. Tallow and palm oil;
4. Babassu;
5. Lard+chicken fat and soybean;
7. Scum, greases, castor bean and sunflower;
11. Brazilnut;
12. Buriti; and
13. Coconut.

–Second assessment: with restrictions:

1. Frying oil and palm oil;
3. Scum and greases;
5. tallow;
5. Lard+chicken fat;
7. Babassu;
8. Castor bean;
9. Soybean;
10. Sunflower;
11. Brazilnut;
12. Coconut oil; and
13. Buriti.

5. Discussion

Table 4 compares the previous results with those obtained in Oliveira et al. [10].

The residues were considered the best sources for biodiesel production by the two articles here compared, followed by the babassu oil, ending with extractives. The big difference is the palm oil position, which was badly ranked in the previous article while emerging in the first position in the present paper. This elapses due to the improvement of the current data, particularly the reduction in value of investment.

Fig. 1 [29] shows that the potential of residual resources (scum, greases, frying oil, tallow, lard, and chicken fat) – around 2.5 billion L – is able to meet Brazil's obligatory demand in the majority of the analyzed period. It is noteworthy that after 2013 it would be necessary to have an additional portion of new inputs. It is

[8] Of which half is allocated to the investment cost.
[9] The efficient options can be ranked according to the number of times they were used as benchmarks for the other production units in each of the three groups analyzed.

Table 3
Efficiency and virtual weights attributed by the model with restrictions on weights (including null value).
Source: VRS Model findings, with restrictions on weights for the unit under analysis.

Alternative energies	Efficiency		Constraints on virtual weights									
			Inputs						Outputs			
			Greenhouse gases emissions (kg CO_2 eq/L)		O&M cost (R$/L)		Investment cost (R$/L)		Potential output (million L/yr)		Potential job generation	
	With	Without	With	Without	With	Without	With	Without	With	Without	With	Without
Lard+chicken fat	0.9379	1	0.3	1	0.2	0	0.5	0	0.5	0.92	0.5	0.0.8
Fryingoil	1	1	0.5	1	0.23	0	0.27	0	0.4	0.19	0.6	0.81
Scum	1	1	0.5	0.98	0.3	0.02	0.2	0	0.4	0.97	0.6	0.03
Tallow	0.9379	1	0.3	1	0.2	0	0.5	0	0.5	0.92	0.5	0.08
Greases	1	1	0.5	0.95	0.3	0.03	0.2	0.02	0.4	0.98	0.6	0.02
Castor bean	0.8026	1	0.2	0	0.3	0	0.5	1	0.5	0.16	0.5	0.84
Soybean	0.7721	1	0.2	0.16	0.3	0.29	0.5	0.55	0.5	1	0.5	0
Sunflower seed	0.7409	1	0.2	0	0.3	0	0.5	1	0.5	0.5	0.5	0.5
Brazilnut	0.5658	0.8352	0.3	0	0.2	0	0.5	1	0.4	0.5	0.6	0.5
Babassu	0.9125	1	0.3	0.96	0.2	0	0.5	0.04	0.4	0	0.6	1
Buriti	0.2876	0.4607	0.5	1	0.3	0	0.2	0	0.4	0	0.6	1
Palm	1	1	0.3	0	0.2	0.19	0.5	0.81	0.4	0	0.6	1
Coconut	0.3343	0.4357	0.5	1	0.2	0	0.3	0	0.4	0	0.6	1

Table 4
Biodiesel production for the Biodiesel National Program. Inputs comparison considering the current work and Oliveira et al. [10].

Ranking	Oliveira et al. [9]	Authors
1	Frying oil	Frying oil and palm oil
2	Scum	
3	Grease	Scum and greases
4	Animal fat	
5	Babassu	Tallow
6	Castor beans	Lard+chicken fat
7	Soybeans	Babassu
8	Sunflower	Castor bean
9	Brazilnut	Soybean
10	Buriti	Sunflower
11	Palm	Brazilnut
12	Coconut	Coconut oil
13	*	Buriti

* The set considered the mineral oil diesel.

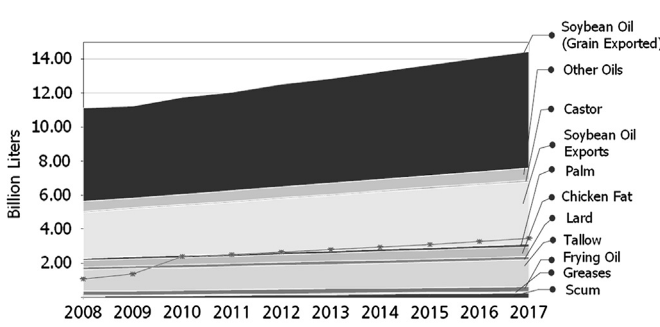

Fig. 1. Potential supply and projected consumption of biodiesel by selected types of residues and vegetable oils, 2008–2017.
Source: Ref. [29].

important to point out that Fig. 1 presents the sources organized by their costs from the bottom (scum is the less expensive) up (soybean oil is the most expensive).

6. Final comments

Although the residues seem the best alternative in terms of socio, economic and environmental sustainability, this option is not as easy to be adopted as the first for various reasons. Some problems of scale and regional differences can affect the residues supplies. It is interesting to pay attention to the different raw materials' participation in the Brazilian production of biodiesel [30]. Soybean oil is the main source, followed by tallow, as shown in Fig. 2.

According to the present work, among all analyzed inputs, soybean oil is not the cheapest, nor does it generates more jobs. Beyond that, it brings less environmental benefits compared to the residues. Nevertheless, the soybean represented around 80% of Brazilian production. There was a time gap between the approval of the Brazilian Law 11.097 which established the National Biodiesel Program, its practical implementation (involving several regulations and normative arrangements) and, finally, the biodiesel effective supply. The goals were considered very difficult to be achieved in the short term. A big effort was required at all government levels and from private sectors to reach the target defined in 5% of biodiesel addition. The favorite source to achieve the demand under these conditions was the soybean. This market has comparative advantages which make it easy to increase it for the Biodiesel program, if the same pattern and regulation conditions are maintained. The soybean market was already established with low costs.

Even with the available amount of the residual resources representing only a very small quantity compared with the Brazilian agricultural potential, the recommendation for its use is based on its immediate availability, its low cost (sometimes negative) and the environmental advantages. It is important to establish the conditions required for biodiesel to become a competitive fuel in Brazil until the production of palm and other oleaginous rises sufficiently to ensure that their market prices become competitive for fuel production. Thus, the use of biodiesel from residual resources can help to promote the National Biodiesel Program, stimulating the use of oleaginous as the primary resource of biofuel production. In accordance with Russo et al. [31], the Biofuels Policy should be directed to stimulate rural economic development and sustainable agriculture in the production of biofuels. Furthermore, supporting policies are important to encourage biodiesel research and promote their prices become

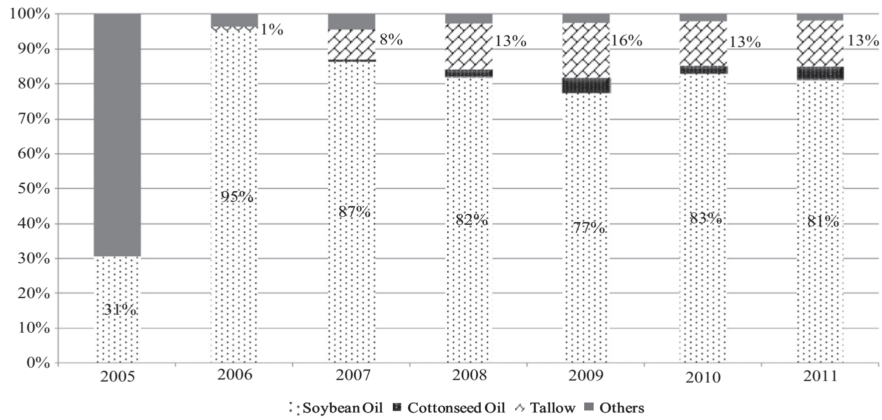

Fig. 2. Participation of inputs in the biodiesel production, 2005–2011.
Source: Authors based on Ref. [30].

more competitive comparing with fossil diesel, as complemented by Atabani et al. [32].

In spite of these problems, it was important to apply the DEA to this case study in order to organize the vast amount of data and sources which the research had to deal with. Therefore, the team took into account the first results obtained by DEA and applied a multi-criteria methodology to go deeper into the analysis. A group of indicators was chosen that could demonstrate the sustainability of the biodiesel production by sources in Brazil.

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